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Composition Optimization of Extrudable Mortar for 3D Concrete Printing

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ABSTRACT

Additive Manufacturing (AM) or 3D concrete printing (3DCP) is a state-of-the-art method for rapidly constructing layer-by-layer structural members with automatic machine control, resulting in significant benefits in the construction field in terms of design flexibility, reduced construction cost, time, manpower, and waste. As a result, the 3DCP is critical to overcoming the housing shortage in many areas and reducing pollution caused by construction activity. This research focuses on an experiment that was conducted to examine the mechanical and fresh mortar qualities of the printer. Experimental trials were used to identify the best water-cement ratios for cementitious materials for the 3D concrete printer. A slump test, flow table test, and vee be Consistometer test are also used to verify the material's suitability for stacking and dispensing. The appropriate sand size for the dispensing mechanism was discovered through experiments. However, shrinkage cracks developed during the hardening process for the paste and mortar, therefore polypropylene fibres were used to avoid cracking and increase the quality of the 3D printed structure. Compressive strength is assessed for the mechanical property after an acceptable and efficient mix ratio is discovered.

The 3D concrete printed components are typically less dense, porous and have shrinkage problem, grey micro silica fume is micro filler material and polypropylene in the cement, along with fly as to extrude a mix. Due to several issues, such as the printer's nozzle being blocked by aggregate, the naturally so-called brittle nature of concrete having relatively low tensile strength and thus at risk of cracking, a problem occurring in compaction, and layer-by-layer issues during placement, conventional mortar or concrete is not a viable material for printing. These issues are overcome by insertion of micro-materials into the matrix of the concrete. Micro-materials, such as micro silica fume, fly ash and polypropylene fiber have ultra-fine particles in the millions.

KEYWORDS: *3D Concrete Printing, Additive Manufacturing, Grey micro silica fume, Polypropylene fiber, Fly-ash, Concrete printing*

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I. INTRODUCTION

Any country's economic development is largely dependent on the Construction industry. Traditional construction, on the other hand, has a number of issues, the most serious of which arespeed and labour efficiency. There are numerous obstacles that must be overcome in order to keep the construction site under control, and physical labour participation causes a number of health-related issues for workers [OSHA US department]. Because construction projects take a long time to complete, the construction industry's biggest stumbling block is the slow pace at which projects are complete. Environmental pollution and carbon emissions are rapidly increasing due to construction industry.

3D printing is also known to as "additive manufacturing (AM)" since it adds material or mix to a product rather than machining or subtracting it. Regardless of the type of material or printer used, 3D printing consists of a few basic stages as shown in figure-1To begin, a designer uses computer-aided design (often referred to as "CAD") to create a three-dimensional design (3D model).

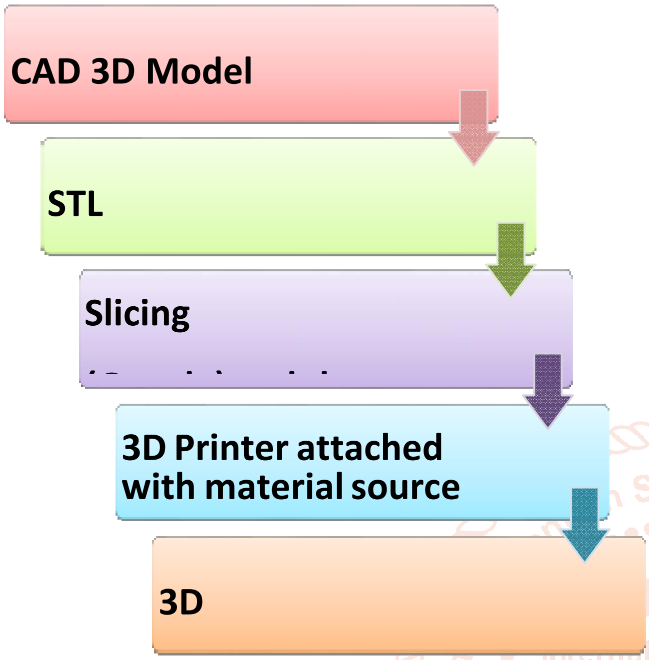

Figure 1: 3D Printing Process

Contour crafting is a fabrication technique invented by Khoshnevis (2004) in California, in which the concrete is carved layer by layer (Perkins and Skitmore, 2015). This is the most promising 3D printing technique since it allows for total house production in situ (Hager, Golonka and Putanowicz, 2016).

II. LITRATURE REVIEW:

Craveiro et al. (2019)

Studied that the digital revolution of the construction area, mainly the perspective of additive manufacturing in building construction as a most significant technology of construction 4.0. The author clears the concept of construction 4.0 and also discussed as well as presented the digital makeover of the construction segment, however, Flávio Craveiro examines additive anufacturing for the construction purpose that permitting engineers and architects to design complex geometries. The author also stated the prime challenges in 3DCP from the viewpoint of fabrication such as to avoid clogs and premature solidification inside the 3D printer, printing time must be reduced. Furthermore, the collision of various-print heads or various robots/gantry systems must be avoided in the case of multiple material depositions, and also the printing of roofs (non- supported structure) or void (doorways, windows, etc.) is quite a huge challenge. To enhance the structural security as well as reliability innovative materials could be established predominantly by means of reinforcement (fiber meshes, fibers, steel, etc.), smart materials likewise self- healing, and shape-memory materials. However research on this topic concludes functionally and lightweight grouped structure, different materials used in additive manufacturing for construction, Flávio Craveiro also presents various research challenges and different processes of printing (Extrusion-based process, Jetting process, Fusion of inflated melting point materials).

Allouzi et al. (2020)

Examine the comparative study between 3D printing and conventional construction on the point of material cost. This research article also targets to the considerate of procedure of 3-D printing, it's mechanism as well as impact through environmental, economic, and structural consideration is accomplished on the upcoming of construction. In this article, Rawan Allouzi compares the traditional construction info of Ras Alain versatile Hall (Jordan) in addition to predictable information if this similar structure would have been built with using 3DCP. The construction cost of Ras Alain Hall by using 3DCP is equaled to 8,872.5 JD (Jordan Dollar) deprived of the insulation work and stone cladding, and construction amount of the same hall by using traditional construction method is 57,947 JD if insulation work and stone clad26,287 JD. So by this evidence of Rawan Allouzi, the concrete cost of Ras Alain Hall based on 3DCP is 8,872.5 JD is fewer than the traditional cost of construction which around 26,287 JD. The study concludes 3DCP diminishes 65% of traditional material costs. The labor costs, equipment cost, and construction time is not considered in this study meanwhile these factors depend on the speed and essential size of a 3-D concrete printer.

Arunothayan et al. (2020)

This paper presents the systematic development and performance characterization of a non- proprietary 3D-printable ultra-high-performance fiber-reinforced concrete (UHPFRC). Several fresh and hardened state properties of the 3D-printable UHPFRC matrix (without fiber) and composite (with 2% volume fraction of steel fibers) were evaluated and compared to that of conventionally mold-cast UHPFRC. Additionally, the effects of test direction on the compressive strength and modulus of rupture of the printed UHPFRC were investigated. The fresh properties of the UHPFRC developed in this study satisfied the criteria for extrudability, build ability, and shape-retention-ability, which are relevant for ensuring printability. The printed UHPFRC exhibited

superior flexural performance to the mold-cast UHPFRC due to alignment of the short fibers in the printing direction. The high compressive and Flexural strength, along with the deflection-hardening behavior, of the developed UHPFRC can enable the production of thin 3D- printed components with significant reduction or complete elimination of conventional.

Khan (2020)

This is a review work done by Khan which aims at reviewing suitable concrete 3D printed mix. From the study of different researchers following observations are drawn- There is a formation of Lubrication layer in the pipe due to segregation of concrete while pumping the mix because of that less pumping pressure is required. The flow ability of concrete is governed by particle size distributions of binder and sand grains. The suitable range of size of fine aggregate is in between 1mm – 2mm. For a mix having low yield stress and dynamic viscosity are helpful in pumpabilty of concrete nut for that same mix there is a problem. Observed in achieving Build ability. There is higher yield stress is observed for a mix having continuous gradation of material. Printable ranges of Plastic viscosity varies between 16.65 to 33.1 Pa-s and Static yield stress within 1.87 to 3.35 kPa.

III. EXPERIMENTAL PROGRAM:

In this Chapter, the characterization of materials used and tests practice have been done and discussed. The properties and specifications of the materials, the mixture quantities, and proportions casting, and curing of the test sample are studied. XRD, RAMAN, SEM were used to study the microstructure of the materials. The focus of this experimental exploration is to find the optimum mix for workability and compressive strength which is suitable for 3D printing.

Act as a binding material in mortar. This is also responsible for the workability of the mix. It combines with water to form a lubricating paste to provide workability to the mix. This paste will make a layer between different constituents to form a homogeneous mix of the different components, as a more free paste is available in the mix more will be the workability. The size of cement particles usually varies between 0.007-0.200 m.

Figure 4.1: Cement

Table: 4.7 Design mix

S No	Cement(g)	Sand(g)	Fly-Ash (g)	Micro Grey silica fume(g)	Water/binderratio	Ppf(g)
1.	5000	5000	0	0	0.45	0
2.	4750	5000	250	0	0.45	0
3.	4500	5000	500	0	0.45	0
4.	4250	5000	750	0	0.45	0
5.	4000	5000	1000	0	0.45	0
6.	4250	5000	500	250	0.45	0
7.	4000	5000	500	500	0.45	0
8.	4240	5000	500	250	0.45	10
9.	4230	5000	500	250	0.45	20

The preparation of the above mix material is done with the help of various research works in the field of optimization of the mix of 3D concrete printing. In the various researches, it was mentioned that the presence of micro fillers and PPF into the mix increases the density of the mix and additionally it will reduce the workability of the mix.

Figure : Dry material for mix and mix procedure

IV. METHODOLOGY:

In this dissertation, study is done mainly focused on to finding the optimum mix and importantfresh and harden properties of mix which is suitable for 3D printer. 3D printed materials are generally less dense, so grey micro silica fume is also used in the mix as a micro filler materialand polypropylene fiber is also used to minimize the shrinkage and micro crack problem. The methodology has been done in the following steps as shown in sections or the flowchart.

Printable material constituents:

Portland Pozzolana Cement, fly-ash, micro silica fume, polypropylene fiber and sand was stocked or reserved at moisture free location or lab. These material are used in for finding the optimum mix which is suitable for 3D printing.

Sand/Binder = 1.0

Water/Binder = 0.45

Fly-ash = variation with 0%,5%, 10%, 15%, 20%

Silica fume /Binder = variation with 0%, 5% ,10%

PPF variation with = 0%, 0.2%, 0.4%, 0.6%, 0.8 %

Direct compressive strength:

Compressive strength is the furthermost valuable factor in any structure. The compressive strength of the materials is to resist the maximum compressive stress under the load applied gradually without the failure of the cause or cause's failure. Tests were performed to determine the strength of PPC in cubes size 70.6mm x 70.6 mm x 70.6 mm as set out in IS 4031: Part 6

Flow Table Test:

The workability of the concrete is one the most potential parameter which will govern some of the most important properties of the concrete used for the purpose of the 3D concrete printing. The workability of the concrete is related to extrudability, buildability, and open-time of the concrete. In the case of 3D concrete printing, the workability can be measured with flow table tests is accordance with the ASTM C230.

Ve-be Time and Remolding Tests:

These tests measure the capability of the concrete to change shape under vibration. In both tests concrete is place in an open-ended truncated cone. The time it takes the concrete to remold itself into a cylinder under vibration, after the cone is lifted away, is the output of these tests.

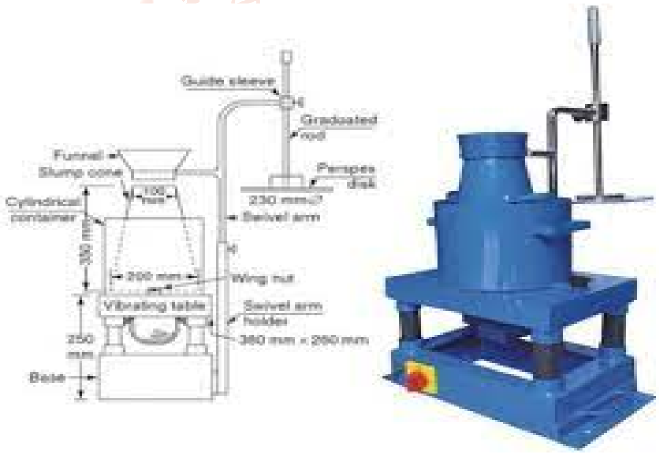

Figure 4.20: ve- be test

V. RESULT AND DISCUSSION

The results and observations obtained from the specified tests stated are presented and discussed in this chapter. Workability and compressive strength of 3D printable mix are discussed. The Grey micro silica fume, PPF and fly ash containing mix were categorized by the concentration ofGrey micro silica fume, PPF and fly ash and also by ratio of sand/cement or binder. These mix samples were examined to obtain the properties includes workability, compressive strength, and open time at different ages. The results are being studied and have

been concluded for the development of manual extrusion mechanism and the mix.

Table 5.6: Average Compressive Strength of samples at 7 days

Mix No.	Compressive Strength of non Compacted cube (Mpa)	Compressive strength of Compacted cube (Mpa)
1.	14.85	18.98
2.	13.52	16.78
3.	12.98	15.65
4.	11.84	13.58
5.	11.32	13.3
6.	14.02	15.18
7.	15.94	17.6
8.	17.1	18.52
9.	17.76	19.78
10.	18.6	22.9
11.	17.6	20.57

Graph 5.2: Average Compressive Strength of non Compacted and Compacted Cube at 7 days

VI. CONCLUSION:

On the basis of above experimental research and study of the results, following conclusions can be drawn

1. The study concluded that 3D concrete printing is the process of layer-by-layer deposition for purpose of converting a designed digital model (CAD file → Mesh file → .stl file → 3D printed component) into the desired structure.
2. The results reveal that incorporation of fly ash in cement mortar improves the workability significantly. Compressive strength increased with curing age for all fly ash replacements. Irrespective of fly ash % the compressive strength decreases at early age when compared to reference mortar. However, at later curing age mortars made with 5%, 10%, 15%, 20% shows higher strength than reference mortar. Maximum efficiency of mortar mix is found at 10% fly ash content.
3. Silica Fume is exceptionally fine, the micro filling effect of silica fume significantly improves the binding of mix and provides more initial strength compared to conventional mortar and prevent the micro cracks. The Optimum Replacement level of cement by silica fume is found to be 5% by weight. There is a significant improvement in the compressive strength of concrete using silica fume at both 7 and 28 days as compare to the referral mortar and reduce the Workability of mix. Beyond optimum levsssel of silica fume decreases the strength.
4. The use of polypropylene fiber affects the workability of fiber reinforcement mortars, polypropylene fibers reduce the workability of mortar mixes and compressive strength of mortar mix increases with increase the fiber content from 0.2%-0.6% and further increase the fiber content it reduce strength of mortar mix. Fiber reduce the cracks and it does not show the cracks on surface of sample after the failure. The Optimum level of polypropylene fiber is 0.6% by weight of binder.
5. In the future, research will mainly focus on the development of 3D concrete printer using robots, optimization of the 3D printable mix, and software design of 3D printing. Though, managing these things and maintaining the quality of the printed structure is the most important and challenging part of Civil engineering.

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